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LEVEL II

# ULF/LOWER-ELF ELECTROMAGNETIC FIELD MEASUREMENTS IN THE POLAR CAPS

by

A.C. Fraser-Smith



Final Report E718-1

December, 1980



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A review is given of the known properties of naturally-occurring ULF/lower-ELF (0.022-100 Hz) electromagnetic pulsations in the polar caps. Because polar cap measurements by Western scientists in this particular frequency range have been surprisingly limited (even when allowance is made for the logistical difficulties), emphasis is given in the review (1) to a description of the gaps in our knowledge of the properties of the pulsations, and (2) to the uniqueness of the geomagnetic field configuration in the polar caps and its implications. Given the gaps in knowledge and the unique field configuration, the opportunities for innovative research on ULF/lower-ELF electromagnetic pulsations in the polar caps appear to be particularly promising.

ACKNOWLEDGEMENTS

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CONTENTS

Note: In this report the abbreviation ULF (ultra-low-frequencies) is used for frequencies less than 5 Hz. Pc 1 geomagnetic pulsations are observed in the upper part of this frequency range (0.2 to 5 Hz). ELF (extremely-low-frequencies) is used to designate frequencies in the range 5 Hz to 3 kHz, and VLF (very-low- frequencies) is used for frequencies in the range 3 to 30 kHz.

# I. INTRODUCTION

Studies of the geographical distribution of ULF/lower-ELF geomagnetic and geoelectric fluctuations, and measurements of their properties at particular geographical locations, provide information about their source regions, generation mechanisms, and modes of propagation. In addition, as our knowledge of the fluctuations increases, the studies and measurements can be used to give diagnostic information, i.e., the dynamic state of the ionosphere, magnetosphere, and solar wind can be investigated by using measurements on the earth's surface [e.g., Troitskaya, 1967; Nishida, 1978], and the structure of the earth can be probed electromagnetically [e.g., Tikhonov, 1950; Cagniard, 1953; Gregori and Lanzerotti, 1980]. Because of their scientific interest and many possible applications, a large number of studies have been made of the various naturally occurring electromagnetic phenomena in the ULF range (frequencies less than 5 Hz; see reviews by Campbell, 1967; Saito, 1969; Jacobs, 1970; and Orr, 1973) and in the lower-ELF range (frequencies in the range 5-100 Hz; see reviews by Campbell, 1967, and Polk, 1974). However there are two geographical regions where, for practical reasons, measurements of ULF/lower-ELF geomagnetic and geoelectric fluctuations are comparatively greatly lacking: the north and south polar caps. This lack is unfortunate, because the polar caps have unique geomagnetic properties and the occurrence of distinctive forms of ULF/lower-ELF geomagnetic and geoelectric activity could be anticipated. Indeed, several new forms of ULF geomagnetic pulsations have already been reported in the two polar caps by Soviet scientists

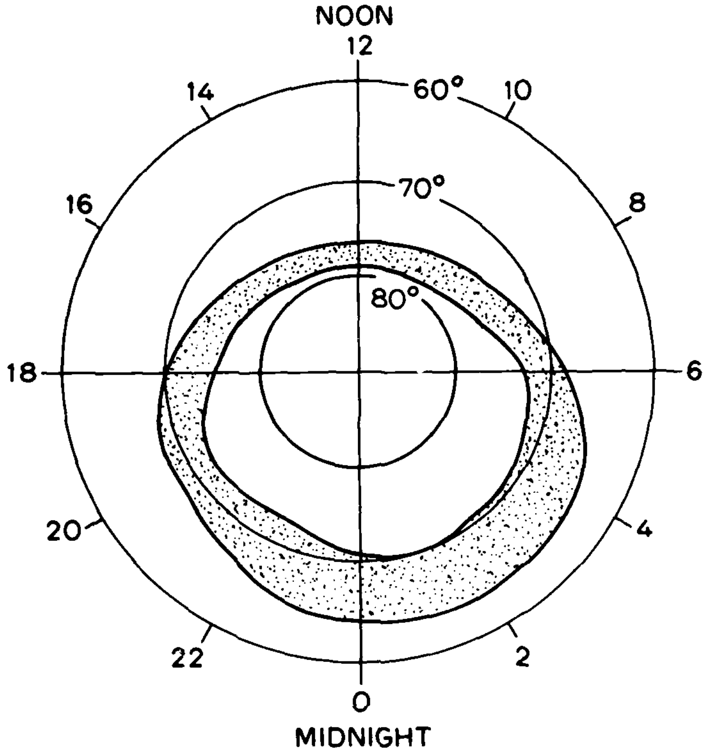


Figure 1. An early statistical representation of the northern hemisphere auroral oval given by Fel'dshteyn [1963]. A geomagnetic latitude/local geomagnetic time coordinate system is used, and the shaded area, representing the auroral oval, indicates the region of most frequent occurrence (occurrence frequency $\geq$ 75%) of auroras in the zenith. Later work has shown that auroral oval contracts towards the poles when geomagnetic activity is low, or expands away from the poles when geomagnetic activity is high. The auroral oval shown in this figure is appropriate for an average state of geomagnetic activity, i.e., for Kp $\approx$ 3.

[e.g., Troitskaya, 1979]. The purpose of this communication is to review the available information of ULF/lower-ELF electromagnetic activity in the polar caps with the aim of stimulating further measurements in these important regions.

There is some ambiguity in the use of the term"polar cap" in the scientific literature. Most commonly it is used to describe one of the two regions (north or south) enclosed by an auroral oval, which means that the auroral oval serves as the basic frame of reference. As defined by Akasofu and Chapman [1972], the oval is the true belt of location of the aurora at any time. It is a continuous band encircling the geomagnetic pole, with its center displaced toward the nightside: in the northern hemisphere its average geomagnetic latitude is roughly 67-68$^{\circ}$ on the nightside and 75-77$^{\circ}$ on the dayside (Figure 1). Two properties of this oval are of particular relevance to this review. First, the earth rotates beneath the oval, and thus it is possible for some high latitude points on the surface (geomagnetic latitude $\sim\pm75^{\circ}$) to be within a polar cap during the night and outside it during the day. Second, the size of the oval (and therefore the size of the polar caps) depends on the state of geomagnetic activity. During very quiet times the oval shrinks, and at midnight the geomagnetic latitude of its outer (equatorward) edge can be greater than 70$^{\circ}$ in the northern hemisphere. When a geomagnetic storm is in progress, the inner and outer limits of the oval shift equatorward, and during very intense storms the oval expands very greatly. Thus the status of a high latitude location may

change from polar cap to auroral oval to subauroral and then back again during the course of an intense storm. These changes, like the diurnal changes, are confined to locations close to the outer edges of the average polar cap (Figure 1). For these locations, a figure prepared by Chubb and Hicks [1970], showing the average geomagnetic latitudes of the equatorward edges of the midday and midnight sections of the auroral oval as functions of the Kp index, is useful for determining whether they have polar cap status during a particular state of geomagnetic activity.

The auroral zone differs from the auroral oval; it is usually defined to be the locus of the average midnight position of auroral activity [e.g., Lanzerotti and Park, 1978], and, when so defined, it is an approximately circular band with an angular width of about $6^\circ$ centered on a geomagnetic latitude of $67^\circ$. The polar caps are sometimes considered to be the areas enclosed by the auroral zones [e.g., Davies, 1969]. However, because of the limited geophysical significance of these zones on the dayside of the earth, an alternate definition of the polar caps appears to be preferable. Another possibility is to take the auroral zones to be the regions of most frequent occurrence of auroras, without reference to time. The auroral zones then extend from about $67^\circ$ to $77^\circ$ in geomagnetic latitude ($-65^\circ$ to $-77^\circ$ in the southern hemisphere), and the polar caps can be defined as the regions enclosed by the inner (poleward) boundary of these auroral zones. Figure 2 shows

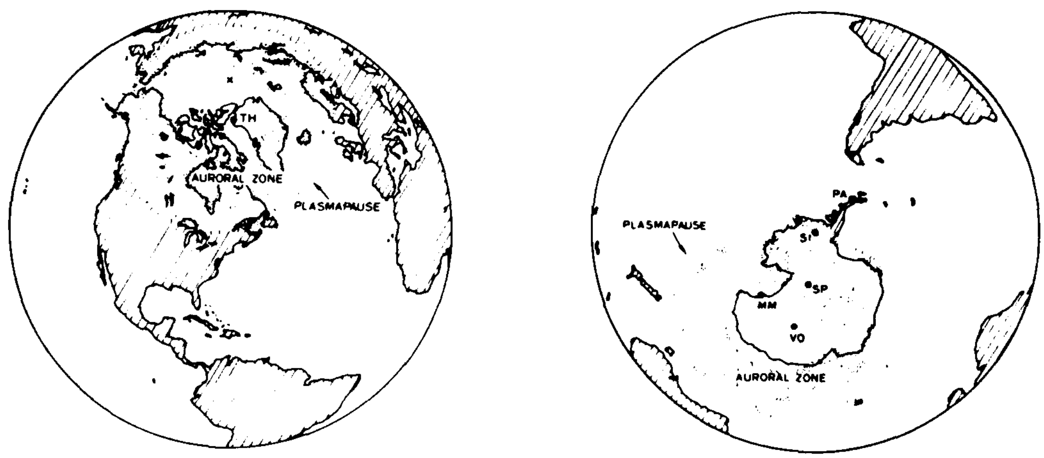


Figure 2. The northern and southern polar regions, showing the polar caps (enclosed by the two auroral zones) and the location of the plasmapause termination in the ionosphere. The geographic north pole is indicated by a small cross; in the southern polar region the Amundsen-Scott station (SP) is located at the geographic south pole. Thule (TH) is close to the geomagnetic north pole and Vostok (VO) is close to the geomagnetic south pole. Other stations shown in the Antarctic are McMurdo (MM), Siple (SI), and Palmer (PA).

the north and south polar caps obtained by this means. They have the advantage of being fixed relative to the earth's surface, in contrast to the polar caps defined by reference to the auroral ovals. The geographical displays in Figure 2 make clear one important point of nomenclature (a point that is independent of the definition adopted for the term "polar cap"): points in the Arctic and Antarctic are not necessarily located in a polar cap. The situation in the Antarctic is perhaps particularly notable, since the Antarctic continent is usually considered to be the epitome of a polar region. As shown by Figure 2, over half of the continent is normally outside the limits of the southern polar cap.

The various definitions of the polar caps, any of which might be encountered in a study of high-latitude ULF/lower-ELF geomagnetic and geoelectric fluctuations, can be put into a unified context by consideration of the high latitude geomagnetic field lines. The polar caps are unique geomagnetically because of the properties of the geomagnetic field lines entering (or leaving) the two regions, and once again it is the auroral oval that provides the frame of reference. The important property of this oval, insofar as this review is concerned, it that its position coincides with the outer boundary of the region of trapped corpuscular radiation in the magnetosphere, i.e., of the region of closed geomagnetic field lines. A schematic drawing of the major regions of the magnetosphere is shown in Figure 3, and it is seen that the geomagnetic field lines passing through the polar caps either extend far out into the tail (where their ultimate fate is controversial, but where

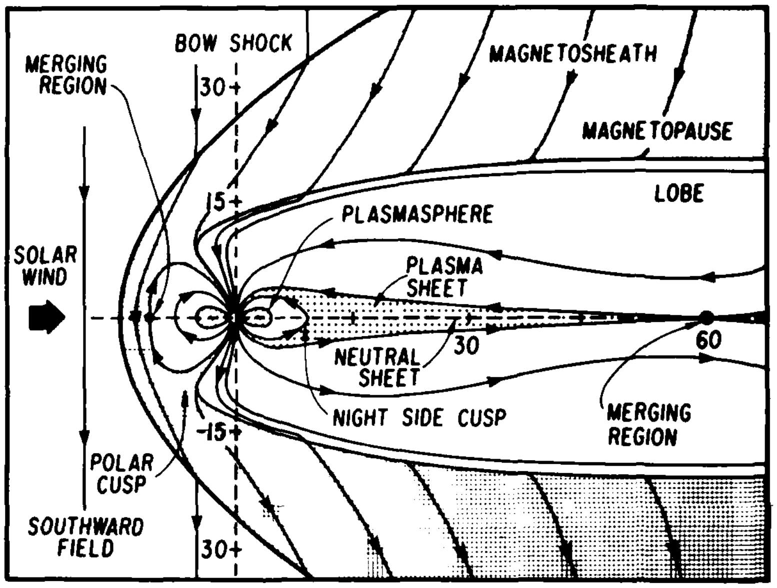


Figure 3. A schematic drawing showing most of the major regions of the magnetosphere. The drawing is roughly to scale and a southward directed interplanetary field is assumed [McPherron, 1979].

they appear most likely to merge into the interplanetary field), or, according to the model of the magnetosphere that is illustrated, they connect comparatively rapidly with the interplanetary field lines. In either case the geomagnetic field line configuration for the polar caps, which is normally described as being "open", is completely different from the closed field line configuration for middle and low latitudes. It is possible therefore to define the polar caps as the two regions on the earth's surface where the geomagnetic field lines are open [e.g., Patel, 1977], and, since it is the most basic, this is the definition that is adopted in this review. Note that the auroral oval and field line definitions for the polar caps are equivalent, and that, in practice, there is little difference between the polar caps given by these definitions and the polar caps shown geographically in Figure 2. (The only difference of significance involves the inner sections of the auroral zones shown in the figure, and it arises because of the geomagnetic activity and day/night shifts in location of the polar cap boundary. The Amundsen-Scott Station [SP; geomagnetic latitude $\sim 74^{\circ}$], for example, is shown within the auroral zone in Figure 2, but it could be classified as a polar cap station when it is on the nightside.)

The geomagnetic uniqueness of the polar caps has been repeatedly emphasized by the Soviet scientists studying high latitude ULF geomagnetic pulsations. For example, Troitskaya et al. [1972] note how "a part of the field lines extending from the polar caps have a direct connection with the magnetopause and the plasma of the solar wind, and,

therefore, information on them is propagated along these lines to the polar caps. These circumstances make surface observations in the polar regions very important." Bol'shakova and Troitskaya [1977] also point out how the polar caps are open for injection of solar corpuscular streams. Several other unusual features of the polar caps should also be mentioned. First, it is well-known that there is a link between polar cap geomagnetic field changes and changes in the interplanetary magnetic field (IMF) sector structure [Svalgaard, 1968; Mansurov, 1969; Wilcox, 1972; and Campbell, 1976]. The frequencies of the observed field changes are generally below the range that will be considered in this review, but observations in the auroral zone [McPherron and Ward, 1967] suggest that some occurrences of higher frequency pulsations in the polar caps may also be linked to sector structure. Second, there is an outward flow of plasma from the north and south polar cap ionospheres into the geomagnetic tail [Banks and Holzer, 1968; and Axford, 1968]. There is no know connection between this "polar wind" and ULF/-lower-ELF pulsation activity in the polar caps at the present time, but a connection is conceivable. Third, as reported by Heacock et. al.[1970] and Afonina and Fel'dshteyn [1971], geomagnetic disturbances occur in the polar regions even when the geomagnetic field is absolutely quiet at middle and low latitudes. Fourth, because of their proximity to the polar cusps (see Figure 3, or Patel [1977]),some of the distinctive pulsation activity associated with the dayside cusp [see Scarf et.at., 1972, 1974; Bol'shakova et. at., 1975; Bol'shakova and Troitskaya,

1977; Kovner and Kuznetsova, 1977; and Temerin and Parady, 1980] is likely to be observed in the polar caps. Much of this activity occurs at frequencies that are too low to be considered in this review, but there appear to be higher frequency components that could be measured. Finally, unlike most other locations on the earth's surface, points in the polar caps have no geomagnetic conjugates, i.e., there are no geomagnetic field lines linking points in the north and south polar caps. This means that conjugate ULF/lower-ELF geomagnetic and geoelectric activity, strictly defined, is necessarily lacking. However, very similar and perhaps identical activity can still occur at both poles when a single large-scale exciting mechanism is involved [Lanzerotti, 1978].

The complete ULF/lower-ELF range (frequencies less that 100 Hz) includes a great many different phenomena and to keep the scope of this review within manageable limits I have restricted it to ULF/lower-ELF geomagnetic and geoelectric phenomena with frequencies in the range 0.022-100 Hz, i.e., ULF phenomena with periods greater than 45 sec are not reviewed. The review therefore covers ELF wave phenomena in the frequency range 5-100 Hz; regular (or continuous) pulsations in the categories Pc 1 (0.2-5 sec), Pc 2 (5-10 sec), and Pc 3 (10-45 sec) [Jacobs et. al., 1964]; irregular pulsations in the category Pi 1 (1-40 sec) [Jacobs et. al., 1964]; Intervals of Pulsations of Diminishing Period (IPDP's; Gendrin et. at., [1967]; and some other special categories of regular and irregular geomagnetic pulsations in the period range 0.2-45 sec. The ELF phenomena are restricted by the choice of frequency to

atmospherics (sferics) and the Schumann resonances. However, the restriction in this case is largely academic because of the lack of studies of lower-ELF geomagnetic and geoelectric fluctuations in the polar caps.

TABLE 1

This table summarizes the period ranges for the various Pc (pulsations, continuous) and Pi (pulsations, irregular) pulsation categories. The first five Pc categories and the first two Pi categories were originally defined by Jacobs et al., [1964], whereas the Pc 6 and Pi 3 pulsations are later additions that were recommended at the 1973 Kyoto Assembly of the International Union of Geodesy and Geophysics/ Association of Geomagnetism and Aeronomy (IUGG/IAGA).

| Pulsation Category | Period Range (sec) | Pulsation Category | Period Range (sec) |
|---|---|---|---|
| Pc 1 | 0.2-5 | Pi 1 | 1-40 |
| Pc 2 | 5-10 | Pi 2 | 40-150 |
| Pc 3 | 10-45 | Pi 3 | $\geq$ 150 |
| Pc 4 | 45-150 | | |
| Pc 5 | 150-600 | | |
| Pc 6 | $\geq$ 600 | | |

## II. BACKGROUND ACTIVITY IN THE POLAR CAPS

In an experimental study of geomagnetic activity in the 0.1-14 Hz band conducted at a midlatitude location, Fraser-Smith and Buxton [1975] divided the geomagnetic activity into two general classes: (1) a class of comparatively stable background activity, where the magnetic field amplitudes drop off with frequency as $f^{-n}$, with $n$ in the range 1.0-1.3, and (2) a class of transient events with center frequencies, bandwidths and durations that vary widely on an event-to-event basis. The latter events rise out of the stable background activity, reach a maximum field strength that can be large in comparison to the background level, and then decay until they finally disappear into the background activity. It was pointed out that the great majority of studies that had been made of geomagnetic pulsations had been concerned solely with events in the second class, and that the activity in the first class had been largely ignored. Unfortunately, the same situation pertains for measurements of ULF/lower-ELF geomagnetic and geoelectric fluctuations in the polar caps, where it could be expected that the linking of the polar cap geomagnetic field lines with the interplanetary field and the magnetospheric tail would ensure a particularly interesting geomagnetic (and geoelectric) background.

Measurements of the lower-ELF background in the polar caps appear to be lacking, and in the ULF band there is only limited information. Most of the studies of background ULF geomagnetic activity [e.g., Stagg, 1935; Mayaud, 1956; Hope, 1961; Yudovich, 1962; and Bobrov et al., 1964] are based on one or another of a variety of range indices, with

the range measured over time intervals varying from 15 minutes up to 3 hours. Range indices of this type are insensitive to pulsations with period of 45 seconds or less, since the amplitudes of ULF geomagnetic fluctuations tend to increase with decreasing frequency (cf.,the results of Fraser-Smith and Buxton [1975] described above) and in intervals of 15 minutes or more it is the fluctuations with periods varying from minutes to hours that largely determine the range of variation of the geomagnetic field. However, there are at least two relevant studies: one by Troitskava et al., [1968], which summarizes results obtained by Hessler at Vostok, and another by Wertz and Campbell [1976], which gives information about the background at Thule (the locations of the two measurement sites are shown in Figure 2).

Troitskaya et al., [1968] comment that "there is a background of micropulsation (the so-called permanent disturbance) during magnetically quiet days of the order of $0.03\ \gamma f$ in summer and $0.005\ \gamma f$ in winter. Note that at 0.1 Hz this corresponds to 0.3 and 0.05 $\gamma$. However, on winter days of low activity the hourly range may be as low as $0.002\ \gamma f$ (0.02 $\gamma$ at 0.1 Hz) almost to the sensitivity limit of the recording system." Interpretation of these results is difficult because they are based on hourly amplitude scalings that were taken without regard to the frequency of the activity. However, it is evident in this case that the data apply at Pc 2-Pc 3 periods. More quantitative data are reported by Wertz and Campbell [1976], who used a power spectrum approach to study geomagnetic field variations in the period range 0.3-300 seconds

at nine widely separated measurement locations. Integrated spectra were computed and used to obtain the mean spectral characteristics of the geomagnetic field variations. Because of the global approach that was taken, the data reported for the two high-latitude locations, the Amundsen-Scott, or South Pole, station (SP) and Thule (TH), are limited. However, Figure 4 shows the average power spectral density at a period of 10 seconds at these locations for the 1972 solstitial and equinoctial months. A summer maximum and a winter minimum at Thule is clearly evident, in agreement with the results of Hessler [1967] and Troitskaya et al., [1968]. However, for the South Pole station, there is also a maximum during the northern summer, i.e., during the southern winter. As was pointed out earlier, the South Pole station is only intermittently in the polar cap, but there appears to be a discrepancy with the Vostok results.

We may conclude tentatively from the above information that there is a noisy geomagnetic (and presumably also geoelectric) background in the 0.2-45 seconds period range in the polar caps that is generally of a somewhat higher amplitude than the corresponding background at middle and low latitudes and which has a seasonal variation with a maximum in the summer and a minimum in the winter. Further studies of this background activity are obviously desirable; it is clear that sensitive measuring equipment must be used, particularly if good measurements are to be made of the low-amplitude winter activity. Also needed is data analysis emphasizing the frequency content of the background

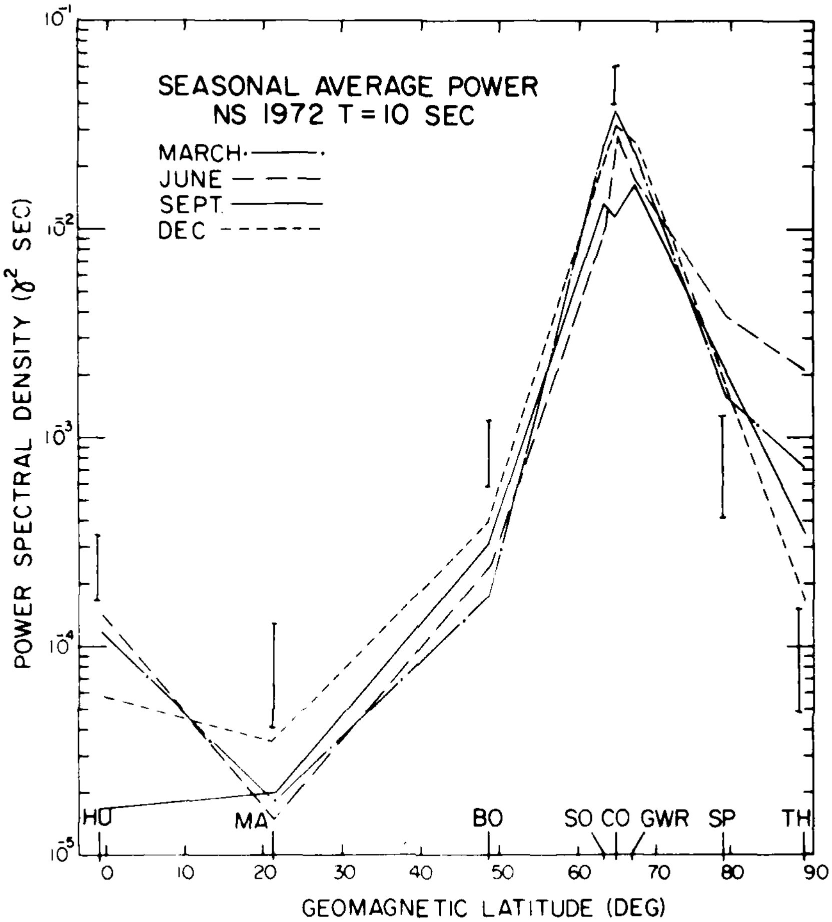


Figure 4. Average 0.1 Hz power spectral densities for March, June, September, and December 1972 at a distribution of stations in geomagnetic latitude. (The station codes are given at the bottom of the figure; the two of importance to this review are SP for South Pole and TH for Thule.) The 10 sec period data apply to the North - South field component. Also shown are error bars representing typical standard deviations. [Wertz and Campbell, 1976.]

fluctuations, i.e., a spectral analysis approach of the kind used by Wertz and Campbell [1976] or by Fraser-Smith and Buxton [1975] at a nonpolar location, which provides quantitative spectral information. Some other studies of geomagnetic pulsations at nonpolar surface locations that had utilized a spectral analysis approach are Davidson, [1964]; Stuart et al., [1971]; Dubrovskiy and Kramarenko, [1971]; Surkan and Lanzerotti,[1974]; and Campbell [1973, 1976], and a useful description of spectral analysis techniques for geomagnetic data is given by Thomson et al., [1976].

## III. PULSATION PHENOMENA IN THE POLAR CAPS

In studying ULF geomagnetic pulsations in the polar caps we are faced by the most complex pulsation situation that is likely to occur anywhere on the earth's surface. As noted by Troitskaya et al, [1968], the same types of pulsations are observed at both geomagnetic poles as are observed at lower latitudes. (There may be trivial exceptions to this rule. For example, pearl-type Pc 1 pulsations with structure doubling [Tepley, 1964], which appear to be necessarily an equatorial phenomenon, have not been observed in the polar caps.) In addition, as discussed in the introduction, new pulsation phenomena can be expected and are observed in the polar caps. The variations of the pulsation phenomena makes review difficult and selection imperative. In the following, I limit discussion to the specific polar cap properties of the established pulsation phenomena and to a description of the pulsations that appear to be peculiar to the polar caps. The review proceeds from low to high frequencies.

### 1. Pc 3 Pulsations (10-45 sec)

One of the most extensive studies of Pc 3 pulsations in the polar caps is that of Troitskaya et al., [1972]. In this study it is emphasized that Pc 3 pulsations "dominate, as regards the frequency of occurrence, all other groups of their family at the geomagnetic poles." This could be taken to imply that Pc 3 pulsations are the most commonly occuring pulsations at the poles and thus, presumably, in the polar

caps. While this conclusion is probably correct for pulsations recorded on slow-speed chart recorders, which usually discriminate against short-period pulsations, it may not be correct for pulsations recorded by other methods. In particular, if the pulsations are recorded on magnetic tape using a system with uniform response over the ULF frequency range and if the data are analyzed subsequently using spectral techniques (i.e., by preparing spectrograms), it is likely that Pi pulsations (a combination of Pi 1 and Pi 2 pulsations) will be found to be the most commonly observed form of pulsations in the polar caps [Heacock, personal communication, 1980]. However, there is no doubt that Pc 3 pulsations occur frequently in the polar caps and in the frequency range under review they are the most commonly occurring class of regular pulsations.

The occurrence properties of Pc 3 pulsations in the polar caps are similar to those observed at lower latitudes: they are predominantly a daylight phenomenon and their diurnal variation of occurrence has a broad maximum that is located a little before local geomagnetic noon [Jacobs and Sinno, 1960; Troitskaya et al., 1972]. Figure 5 shows this local time dependence in greater detail for Vostok. There is also a seasonal variation of occurrences which in the case of the polar caps is also closely tied in with the variation from day to night. At Vostok the rate of occurrence is almost three time greater in December (daylight) that it is in June (night). The June seasonal variation, displaced by six months, should also be observed at Thule.

Figure 6 shows the individual average monthly Pc 3 amplitudes at

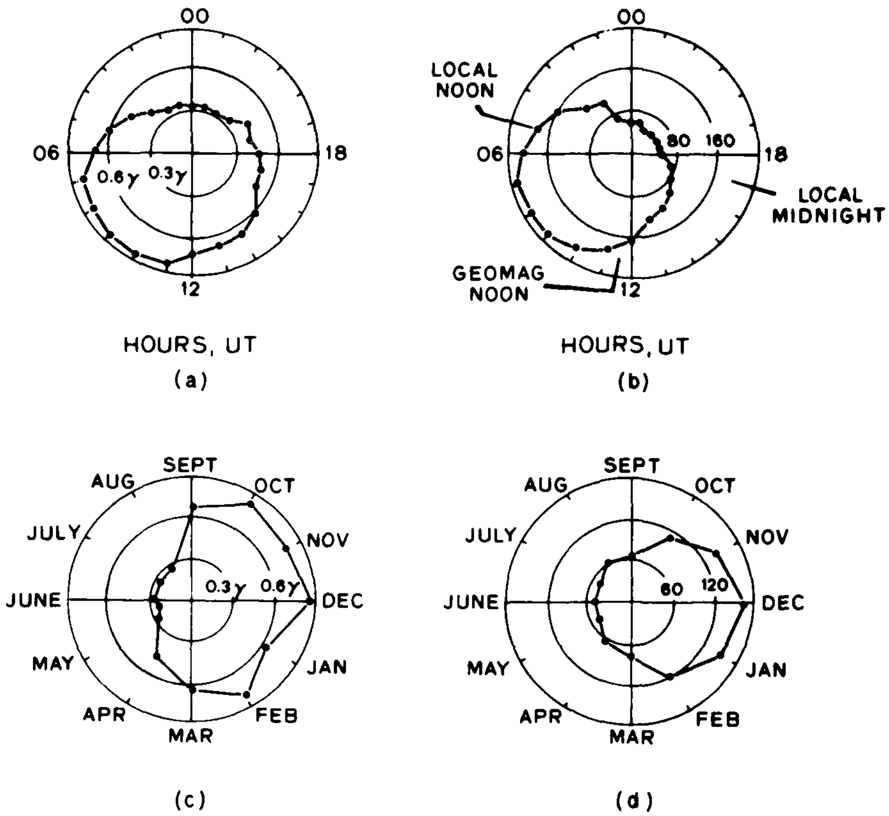


Figure 5. (a, b) Local time and (c, d) seasonal dependence of (a, c) amplitudes and (b, d) occurrence frequencies for Pc 3 pulsations measured at Vostok, Antarctica [Troitskaya et al., 1972; Lanzerotti, 1978].

Vostok for the years 1965 - 1969 that were used to derive the average variation in Figure 5. In addition to the well-defined seasonal variation, which Figure 5 summarizes, these data show that there was no obvious overall change in Pc 3 amplitudes during the five-year interval of observation. This result probably implies that the solar cycle change of Pc 3 amplitudes is insignificant, as Troitskaya et al., [1972] conclude, but more observations are desirable before such a variation can be dismissed with certainty.

Insofar as the relative amplitudes of the polar cap Pc 3 pulsations are concerned, it is clear that the maximum amplitudes are reached at a geomagnetic latitude of about $70^{\circ}$ [Troitskaya et al., 1972; Baranskiy et al., 1973, 1974; Buloshnikov et al., 1977] which, at best (local midnight), is at the equatorward edge of the polar caps (Figure 1). As shown by Figure 7, the average amplitude of Pc 3 pulsations appear to decline rapidly as the point of observation moves away from the polar cap boundary toward the geomagnetic poles and at the poles the average amplitudes is no greater than the value at middle and low latitudes.

The Pc 3 pulsation period range extends from 10 to 45 seconds, but at both geomagnetic poles the most common periods observed by Troitskaya et al., [1972] were in the range of 25-35 seconds. These authors also found that there was no evidence for a solar cycle variation of period, but once again it must be pointed out that this result was obtained with less than a full solar cycle interval of data.

A unique feature of the polar caps, or of high geomagnetic latitudes

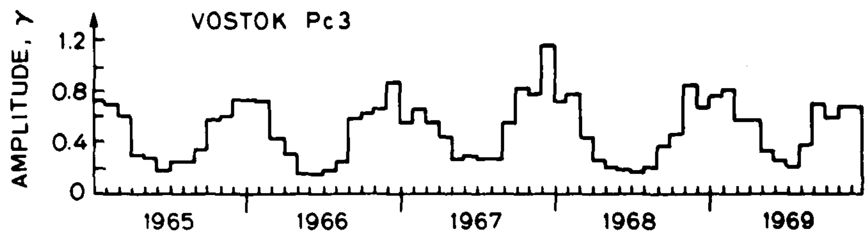


Figure 6. Monthly average Pc 3 pulsation amplitudes measured at Vostok, 1965 - 1969 [Troitskaya et al., 1972; Lanzerotti, 1978].

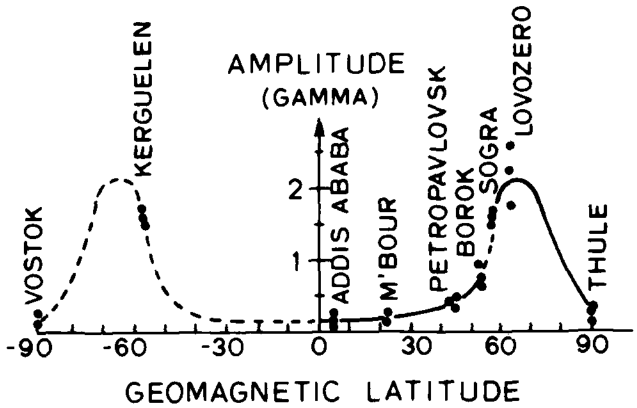


Figure 7. Variation of the average amplitude of Pc 3 pulsations with geomagnetic latitude, [Troitskaya et al., 1972].

in general, is the occurrence of polar cap absorption (PCA). This is basically a radio propagation phenomenon [Reid, 1978] and it is therefore largely irrelevant to this review. However, PCA's are caused by an influx of energetic particles into the polar ionosphere and it is interesting that Fraser-Smith and Helliwell [1980] have observed the appearance of Pc 3 pulsations at the start of a PCA event. The observation was made at an auroral zone station, but if it is indicative of a general relation similar observations should be possible in the polar caps.

## 2. Pc 2 Pulsations (5 - 10 seconds)

When the Pc 2 pulsation period range was first defined [Jacobs et al., 1964] it was observed that "their properties have been but little investigated, but they do not seem to be physically related to those micropulsations in classes Pc 1 and Pc 3." This class of pulsations is still comparatively neglected and at midlatitudes it is often combined with the Pc 3 category, even though studies have shown that the Pc 2 pulsations are predominantly a nighttime phenomenon [Jacobs, 1964] and, as described in the previous section, Pc 3 pulsations typically occur during the day. Although undistinguished at middle and low latitudes, the Pc 2 pulsations form a distinctive class of ULF activity at auroral and polar cap locations. They are observed more often in the polar caps than anywhere else, and, partly for this reason, it has been suggested

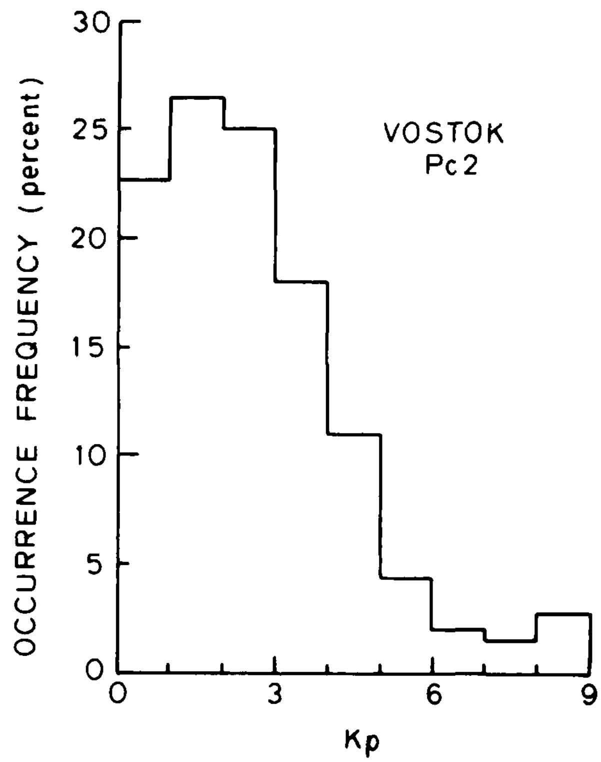


Figure 8. Variation of the frequency of occurrence of Pc 2 pulsations at Vostok with the level of general geomagnetic activity (as measured by the Kp index). The occurrence frequency is given in the form of a percentage of the total occurrences in the data sample [Bol'shakova and Gul'yel'mi, 1972; Troitskaya et al., 1972].

that they reach the earth in the polar caps after having been generated at a considerable distance from the Earth in the geomagnetic tail [Bol'shakova and Gul'yel'mi, 1972; Troitskaya et al., 1972].

In their discussion of the question of the possible location of the source of Pc 2 pulsations, Bol'shakova and Gul'yel'mi [1972] provide some useful but limited information about these pulsations in the polar caps. For example, they show that Pc 2 pulsations occur most frequently for Kp $\leq$ 2 (Figure 8), which is different from the situation at mid-latitudes. Also, they quote the following preliminary results: (1) at low Kp levels, the amplitude of Pc 2 pulsations at the geomagnetic poles can be several times larger than the amplitude of simultaneously observed Pc 2 pulsations at middle latitudes; and (2) at high Kp levels the amplitudes of simultaneously observed Pc 2 pulsations are comparable at the poles and at midlatitudes, but the amplitudes usually do not exceed those observed at the pole on geomagnetically quiet days.

Apart from the observation that Pc 1 - 2 pulsations tend to occur most often in the summer (daylight) months at the geomagnetic poles [Heacock et al., 1970], which might be interpreted to apply specifically to Pc 2 pulsation, and that Pc 2 pulsations with a repetitive rising-frequency fine structure similar to that observed in structured Pc 1 pulsation events are not uncommon at auroral zone locations but are not usually recorded in the polar caps [Heacock et al., 1970], little other information is available on polar cap Pc 2 pulsations. Obviously lacking are details of the occurrence frequency and typical amplitudes

specifically of Pc 2 pulsations in the polar caps, as well as the diurnal and seasonal variations of these properties of the pulsations. (Summer maximums in occurrence and amplitude can be inferred from the work of Heacock et al., [1970], but additional measurements specifically on Pc 2 pulsations are still needed). Finally, as suggested by Heacock [personal communication, 1980], there is a possibility that some of the Pc 2 activity occurring in the polar caps originates as Pi 1 pulsations and is shaped into the more-regular Pc 2 form by horizontal propagation in the F-layer ionospheric waveguide [Greifinger and Greifinger, 1968]. Investigation of this possibility with a chain of stations suitably located in one of the polar caps would add to our knowledge of both Pc 2 and Pi 1 pulsations.

### 3. Pc 1 Pulsations (0.2 - 5 Hz)

These pulsations have been variously called pearls, hydromagnetic emissions, continuous sub-ELF emissions, and type A oscillations [see Tepley and Amundsen, 1965]. More recently, as use of the Pc 1 notation has become standardized, Pc 1 pulsations have been divided into two categories according to whether their frequency-time displays have a periodic frequency structure (structured Pc 1) or lack this structure (unstructured Pc 1) [see Heacock and Akasofu, 1973]. The division into these two categories is supported by evidence that the two kinds of pulsations represent different phenomena.

At high latitudes, as at other latitudes, the two categories of pulsations have many properties in common, as well as having important differences in their properties. Insofar as their origin is concerned, it appears that the pulsations share a common characteristic: neither class of pulsation originates in the polar caps (or, equivalently, on the open field lines intersecting the polar caps). Many investigations have shown that the structured Pc 1 pulsations must originate on closed geomagnetic field lines, and thus, to reach the poles, the hydromagnetic waves producing the pulsations must propagate poleward through the F-layer ionospheric waveguide [Heacock et al., 1970]. Is is not yet clear where the unstructured Pc 1 pulsations originate, but nearly all Pc 1 pulsation amplitudes at polar sites are small compared with their amplitudes at auroral zone locations, which suggests that the unstructured Pc 1 pulsations, like their structured counterparts, are not generated on the open field lines intersecting the polar caps. Additional support for this conclusion is provided by the observation that many structured Pc 1 pulsation events contain unstructured portions, which obviously implies that some unstructured Pc 1 activity originates on closed field lines [Heacock et al., 1970].

The first study specifically of Pc 1 pulsations in the polar caps was made by Wescott et al., [1966]. Only a few months of data were analyzed and the results were preliminary. It was reported that structured Pc 1 pulsations occurred quite commonly near the geomagnetic poles and that they occurred most often and with greatest amplitude during the

daytime. Unstructured Pc 1 pulsations were also observed, but they occurred less often and almost always during the day.

Following this start, more extensive studies of Pc 1 pulsations in the polar caps were reported by Troitskaya [1967], Troitskaya et al., [1968], Heacock et al., [1970], and Heacock and Kivinen [1972]. The greater quantity of data that was analyzed allowed the diurnal and seasonal variations of occurrence of both structured and unstructured Pc 1 pulsations as well as other properties of the pulsations, to be determined with considerable confidence. The following summary of the properties of polar Pc 1 pulsations is derived largely from these latter sources.

Contrary to the preliminary results of Wescott et al., [1960], it is found that structured Pc 1 pulsations occur most often during winter at the geomagnetic poles, when the polar regions are in continual darkness, and that comparatively few of thse pulsations occur during the summer months, when the polar regions are in continual daylight. Heacock et al., [1970] report a factor of ten difference between the winter and summer occurrences in their measurements and they describe the seasonal variation as being "extreme".

During both winter and summer there is only a small diurnal variation in the occurrence of the pulsations. However, during spring and fall there is a well-defined diurnal variation with a minimum in the number of occurrences around local geomagnetic noon and a maximum around midnight [Heacock et al., 1970; Heacock and Kivinen, 1972].

The diurnal variations obtained by Heacock and Kivinen [1972] for Thule are shown in Figure 9.

As pointed out by Heacock et al., [1970], the combination of small winter and summer diurnal variations and pronounced seasonal variation is consistent with the expectation that the structured Pc 1 pulsations reach the poles via horizontal hydromagnetic propagation in an F-layer ionospheric duct [Manchester, 1966; Tepley and Landshoff, 1966; Greifinger and Greifinger, 1968]. It would be expected, as a result of this propagation, that the amplitudes of the structured Pc 1 pulsations would be smaller in the polar caps, and near the geomagnetic poles in particular, than the amplitudes in the auroral zones, where the feet of the source field lines are generally thought to be located [Jacobs, 1970]. These smaller amplitudes were observed by Heacock et al.,[1970]: During two winter months of observations near the north geomagnetic pole, the same number of structured Pc 1 pulsation events were observed at the polar station as were observed at College, Alaska (an auroral zone station), but the amplitudes near the pole were an order of magnitude smaller than at College. The latter authors also report that most structured Pc 1 events observed at the polar location had amplitudes less than 10 m$\gamma$ and that the largest event observed in several years of recording had an amplitude of only 200 m$\gamma$, which should be compared with amplitudes of over 1$\gamma$ that were frequently observed at College.

Unstructured Pc 1 pulsations differ strikingly from the structured pulsations in their seasonal variation at the geomagnetic poles. Their

occurrence rate and amplitudes both reach a maximum during the summer months and summertime amplitudes of $1 \gamma$ or more are not unusual [Heacock et al., 1970]. Even in winter, when their rate of occurrence is comparatively low, the amplitudes of the unstructured Pc 1 pulsations are an order of magnitude larger than the amplitudes of the structured pulsations. Contrary to the situation for these latter pulsations, both the rate of occurrence and the amplitudes of unstructured Pc 1 pulsations tend to be greater at the geomagnetic poles than at auroral zone locations [Heacock et al., 1970]. Remembering that the rate of occurrence and amplitudes of Pc 1 pulsations in general decline at latitudes below the auroral zones, it appears that unstructured Pc 1 pulsations are predominantly *a polar* cap phenomenon.

There are interesting and as yet incompletely explained limitations on the frequency ranges covered by structured and unstructured Pc 1 pulsations in the polar caps. Troitskaya [1967] was one of the first to comment on these limitations: "Investigations at high latitudes and at the polar caps -- have shown that the fine structure typical for the Pc 1 series is more characteristic for pulsations with periods less than 3 sec. Pulsations with periods from 3 to 8 sec, which predominate at high latitudes, do not always have this property." In agreement with these observations, Heacock et al., [1970] found that most unstructured Pc 1 pulsations occurring at a location near the north geomagnetic pole had frequencies less than 0.5 Hz; no Pc 1 events of either category with frequencies above 2 Hz were observed. Heacock and Kivinen

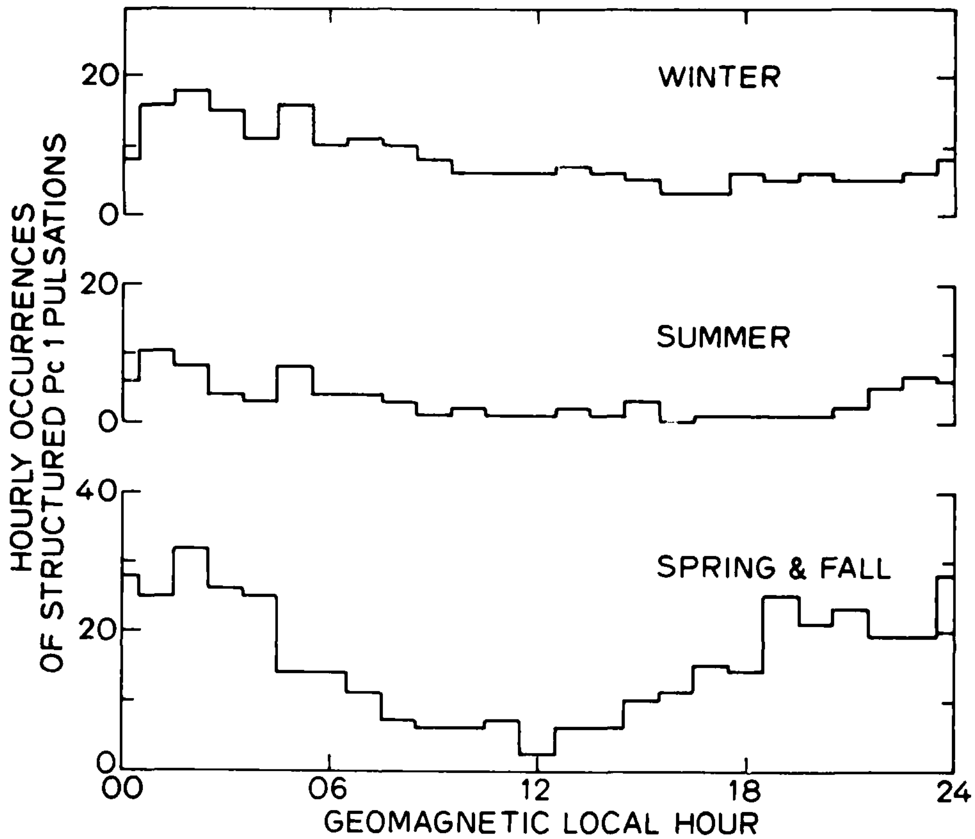


Figure 9. The daily variation in hourly occurrences of structured Pc 1 pulsations as measured at Thule, Greenland, during the winters of 1967 - 1968 through 1969 - 1970, the summers of 1968 and 1969, and the spring and fall quarters of 1968 and 1969 [Heacock and Kivinen, 1972].

[1972] further refined the known frequency range for structured Pc 1 pulsation occurrences at the geomagnetic poles when they reported that hardly any of these pulsations were observed at Thule with frequencies below 0.3 Hz. The frequency range for structured Pc 1 pulsations at the poles is therefore quite strongly limited to 0.3 - 2 Hz, whereas unstructured Pc 1 pulsations, while subject to the same upper frequency limit, occur with center frequencies all the way down to the nominal 0.2 Hz lower frequency of the Pc 1 range. Considering the close similarity between these unstructured Pc 1 pulsations and Pc 2 pulsations (0.1 - 0.2 Hz) in the polar caps, it appears that the 0.2 Hz separation frequency has no physical significance for unstructured pulsation activity and that Pc 2 pulsations and *unstructured* Pc 1 pulsations are simply the lower and higher frequency forms of one distinctive category of polar cap pulsation activity covering the frequency range 0.1 - 2 Hz (and which, incidentally, occurs most prominently when geomagnetic conditions are moderately quiet [Heacock et al., 1970]).

Studies appear to be lacking of the spatial variation of Pc 1 pulsation frequencies (or other Pc 1 pulsation characteristics) across the polar caps: measurements have been made at the geomagnetic poles and in the auroral zones, but at few locations in between. Thus, measurements at even a single location between one of the geomagnetic poles and the poleward boundary of the adjacent auroral zone could provide useful new pulsation data. However, operation of a chain of stations between the pole and auroral zone would provide better information

because of the possibility of large spatial gradients occurring in the measured properties of the pulsations; particularly in the vicinity of the cusps. The existence of these large gradients can be inferred from some of the results obtained by Heacock et al.,[1970] at College, Alaska, and at Bar I, Canada, which is $6^{\circ}$ N of College and nearly on the same geomagnetic meridian. Heacock and his coworkers found that there was a much closer resemblance between the activity at Bar I and the north geomagnetic pole (separation $\sim 20^{\circ}$ of geomagnetic latitude) than there was between the activity recorded at Bar I and College.

Although the polarization characteristics of unstructured Pc 1 pulsations do not appear to have been studied in the polar caps, measurements of the polarization of structured Pc 1 pulsations have been reported by Hessler et al., [1972a] for Vostok. It was found that in most events the activity was approximately linearly polarized in the horizontal plane, as would be expected if propagation in the F-region ionospheric duct was involved [Greifinger and Greifinger, 1968]. Hessler et al., [1972a] also observed some elliptically polarized events, which they interpreted as being caused by the superposition of two or more linearly polarized events. Insofar as the polar caps in general are concerned, the approximate linear polarization of the structured Pc 1 events at the poles should become more and more approximate and perhaps finally disappear as the point of observation approaches the edge of polar caps. Interestingly, the vertical component of the pulsation magnetic fields was found by Hessler et al., [1972a] to be

relatively small at Vostok, which would be expected if the subsurface was a good conductor. A similar small vertical magnetic field component should also be observed in the northern polar cap.

## 4. Miscellaneous Pulsations in the Pc 1 - 2 Frequency Range (0.1 - 5 Hz)

In addition to the standard Pc 1 and Pc 2 pulsations, and the irregular pulsations Pi 1 (which will be reviewed in the next section), there are a number of other types of pulsations that occur in the frequency range 0.1 - 5 Hz in the polar caps. In many cases these pulsations are sufficiently distinct to have been given specific names and the majority appear to be unique to the polar regions. The best known of these pulsation phenomena are called IPDP (Irregular Pulsations of Diminishing Period); the others may be described variously as IPRP (Intervals of Pulsations of Rising Period), PVP (Pulsations of Variable Period), serpentine emissions, sporadic emissions, and discrete bursts (or Pc 1b). These pulsations will now be briefly described.

4.1 IPDP (Irregular Pulsations of Diminishing Period). This particular pulsation phenomenon has been extensively studied at auroral and midlatitudes since its first identification by Troitskaya [1961]. A typical IPDP event consists of a more or less narrow band of ULF noise ($\Delta f \sim 0.3 - 0.6$ Hz) whose mean frequency increases suddenly (typically from 0.5 to 1.5 Hz in 30 minutes) [Gendrin et al., 1967; Gendrin and

Lacourly, 1968]. Although they are not usually included in the formal definition, scattered rising frequency elements similar to the repetitive rising times that characterize spectrums of structured Pc 1 pulsations are sometimes also observed in association with the noise band of IPDP.

IPDP are rarely observed in the polar caps. Shchepetnov and Kalisher [1968], for example, found that a single IPDP event they studied was not distinct at two high latitude stations, even though it was clearly seen at lower latitudes. In a more extensive study, Heacock et al., [1970] observed only one well-defined IPDP event during several years of observations near the north geomagnetic pole. Clearly, IPDP are not a significant pulsation phenomenon in the polar caps.

There is another pulsation phenomenon which may be called IPIP (Irregular Pulsations of Increasing Period) by analogy with IPDP, which it resembles closely except for the fact that its mean frequency decreases with time [Gendrin et al., 1968]. These pulsations are only rarely observed and,as far as I am aware, they have never been reported in the polar caps. They are included in this review because of the possibility that they could be confused with IPRP, which, as described in the following section, are a completely distinct pulsation phenomenon.

4.2 IPRP (or PVP). These pulsations were discovered comparatively recently [E.T. Matveyeva, Dissertation, Moscow, 1970] and they have since been extensively studied by Soviet investigators [e.g. Matveyeva

et al., 1976b]. Apart from the possible confusion with IPRP referred to above, a difficulty with nomenclature could arise in the case of this pulsation category because of the use of the two abbreviations IPRP and PVP to indicate the same pulsation phenomenon (compare Matveyeva et al., [1976a] with Matveyeva et al., [1976b]). I will use IPRP to describe these pulsations.

IPRP consist of a sequence of bursts (or wavepackets) of quasi-sinusoidal pulsations having a typical duration of 3-5 minutes and a mean period in the range 1-8 seconds [Matveyeva et al., 1976 a,b]. Their properties have recently been summarized by Troitskaya [1979]: (1) Their maximum amplitudes occur in the vicinity of the cusps, (2) their occurrence rate at polar observatories has both a diurnal and a seasonal variation, with maximums around geomagnetic noon and the solstices, respectively, and (3) they occur most often when Kp is the range 0-3, and thus they occur much less frequently during years of high solar activity [Matveyeva et al., 1976 a,b]. Their occurrence is usually preceded by geomagnetic field disturbances, although, as indicated above, the IPRP themselves tend to occur during periods of low or moderate goemagnetic activity: more than 70% of the IPRP events observed by Matveyeva et al., [1976 a,b] took place either during the recovery phase of a geomagnetic storm or during the quiet days following a disturbance. It may be of interest that this latter property of the IPRP implies that they should be predictable on a short term basis [Fraser-Smith, 1980].

Spectrograms of IPRP events show that the waves in the separate wavepackets typically have a declining frequency. This is the reason of course for the designation IPRP. However, increasing and intermediate tones are also observed occasionally [Matveyeva et al., 1976 a,b]. At polar observatories the initial IPRP period has an average value of about 2.8 sec and the average final period is about 4.4 sec.

The number of bursts (or wavepackets) in an IPRP event is typically in the range 1-6, although a single burst is most common, and the spacing between the bursts can range from several minutes to one hour or more [Matveyeva et al., 1976, a,b].

IPRP can be observed simultaneously over a large area, but their amplitudes decline away from the cusps (where amplitudes in the range 0.2 - 1$\gamma$ are not uncommon) and they occur much less often at midlatitudes than they do at high latitudes [Matveyeva et al., 1976 a,b]. They also appear to occur less often at the geomagnetic poles than they do at the cusps (although this is not stated explicitly in the available literature) and their average amplitude at the poles is about 0.01 $\gamma$. In view of the considerable decline of amplitude of the IPRP between the cusps and their adjacent geomagnetic poles, the pulsations are not as markedly a polar cap phenomenon as unstructured Pc 1-2 pulsations. However, it may not be inaccurate to state that IPRP are typical of the polar caps [Matveyeva et al., 1976 a,b]. Further studies of this interesting new class of pulsations are desirable.

4.3 Serpentine Emissions (SE). These are another recently discovered pulsation phenomenon. Interestingly, they were first identified in geomagnetic pulsation data recorded at Vostok [Gul'yel'mi and Dovbnya 1974]. The emissions derive their name from their appearance on a spectrogram: they consist of a winding dark band with a width of about 0.2 Hz that may persist for many hours or even up to a day or more [Gul'yel'mi and Dovbnya, 1974; Troitskaya, 1979]. Figure 10 shows an example of one of these SE and compares its UT frequency variation with the variation of the AE index of geomagnetic activity; in the example shown there is a correlation between the frequency variation and AE. As pointed out by Gul'yel'mi and Dovbnya [1974], the SE occurs in the frequency range 0-2 Hz, which leaves open the possibility that they occur at frequencies below the Pc 1 - 2 range. However, from other results cited in the latter paper, it appears that the frequency range of SE rarely extends much below 0.1 Hz and that the pulsations are mostly confined to the frequency range 0.1 - 1.2 Hz.

It is tempting to consider the SE to be a variety of unstructured Pc 1-2 pulsations and there are some similarities. The frequency ranges are similar, for example, and both SE and unstructured Pc 1 pulsations tend to occur most prominently when the Kp index of general geomagnetic activity is low [Gul'yel'mi and Dovbnya, 1974; Heacock et al., 1970]. However, as pointed out by Gul'yel'mi and Dovbnya [1974], the SE are distinguished from other pulsations in the same frequency range by the intense modulation of their "carrier frequency": the mean

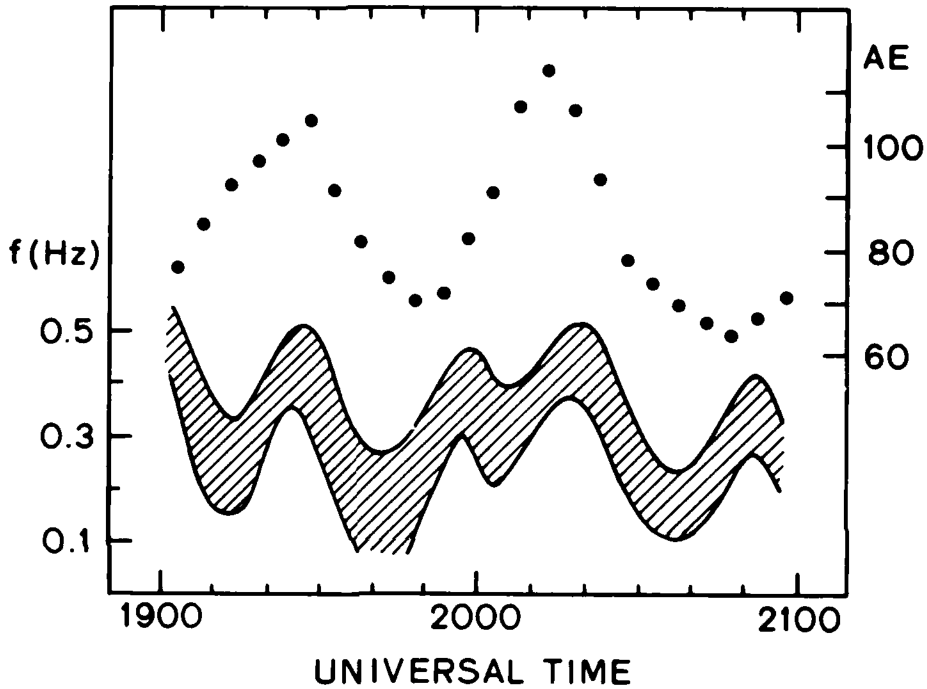


Figure 10. Frequency display showing the approximate variation of the mean frequency and frequency spread of a "serpentine emission" recorded at Vostok on 7 March, 1968. Also shown (right hand scale) is the simultaneous variation of the AE index [Gul'yel'mi and Dovbnya, 1974].

frequency varies from a maximum of ~1 Hz to a minimum of 0.1 Hz with a quasi-period in the range of 10-60 min. in typical examples of SE observed at Vostok. Another difference is a summer minimum and winter maximum in the occurrence of SE versus an opposite variation for unstructured Pc 1 pulsations (the SE do not have a clearly defined diurnal variation in either their mean emission frequency or modulation period [Gul'yel'mi and Dovbnya, 1974]).

Comparative measurements of SE over a wide distribution of stations in the polar cap and auroral zones are lacking and, until further studies of the SE are carried out, it is impossible to say whether they are solely a polar cap phenomenon. However, Gul'yel'mi and Dovbnya [1974] suggest that the SE are generated in the interplanetary medium as a result of a cyclotron instability. If so, the pulsations are likely to be observed more frequently and with greater amplitudes in the polar caps than elsewhere. This is another new class of pulsations in the Pc 1 - 2 frequency range that deserves further study.

4.4 Sporadic Emissions. These pulsations, which were first reported by Dacosta and Dovbnya [1974] in Vostok data, occur predominantly in the frequency range 0.1 - 0.7 Hz and consist characteristically of a broadband burst at the instant of a geomagnetic storm sudden commencement (SSC) followed by a weaker narrowband continuous emission. A typical sporadic emission event lasts for about 1-2 hours. This is another polar cap pulsation phenomenon that has received little study,

although it should be pointed out that the pulsations accompanying SSC have been studied extensively at lower latitudes [e.g., Heacock and Hessler, 1965]. The following brief description of the emissions (and the definition given above) is based on the work of Dacosta and Dovbnya [1974].

Considering the frequency characteristics of the emissions in greater detail, it is found that the average frequency of the initial broadband burst is about 0.4 Hz, its bandwidth is typically in the range 0.4 - 0.6 Hz, and its duration is typically about 5 min. The average frequency of the subsequent continuous emissions is about 0.25 Hz and it is thus somewhat lower than that of the initial burst. These emissions last much longer (typically 1-2 hours) than the bursts and their bandwidth is about 0.1 Hz. Sometimes a series of discrete elements appear instead of the continuous emissions.

Dacosta and Dovbnya [1974] point out that the sporadic emissions are generally preceded by several hours of low magnetic activity, which suggests that not all SSC's are accompanied by a sporadic emission in the polar caps. In fact, many of the statistics of these emissions are lacking, and the determination of these statistics could well be the subject of a further study. Also lacking are details of the seasonal variation, if any, and the variation of the emission characteristics over the polar caps. There appears to be a well-defined diurnal variation, since Dacosta and Dovbnya [1974] report that in most of the cases they examined the sporadic emissions were observed at night at Vostok.

Partly for this latter reason, Dacosta and Dovbnya [1974] deduce that the emissions appear most likely to originate in the tail of the magnetosphere.

4.5 Discrete Bursts (Pc 1b). These pulsations were first reported by Matveyeva and Troitskaya [1965]. A typical Pc 1b event consists of a single burst of pulsations lasting from 1-4 min., depending on the pulsation period, which is usually about 3-4 sec. but which can vary in the range 1-4 sec. Matveyeva et al., [1978] studied the properties of these pulsations in some detail and a summary is given by Troitskaya [1979]. The following brief review is based on these sources.

Pc 1b pulsations (the b in this notation denotes "burst") are not a characteristic polar cap pulsation phenomenon in the sense that their maximum amplitude occurs at geomagnetic latitudes in the range $70^{\circ}$ - $74^{\circ}$. Their first observation appears to have been midlatitude station Borok [Matveyeva and Troitskaya, 1965] and on occasion it is possible for particular Pc 1b events to be observed at midlatitude stations but not at high latitudes. However, Troitskaya [1979] includes Pc 1b in her list of geomagnetic pulsations that are specific to the polar caps, which suggests that they are widely observed throughout the caps. In addition, Pc 1b pulsations have diurnal variation with a daytime (local geomagnetic time) maximum amplitude. This daytime maximum, in combination with the observed latitude range for maximum amplitude,

suggests that the Pc 1b orginate either in or in association with the daytime cusps. If so, they are indeed likely to be frequently observed in the polar caps.

The Pc 1b pulsations are usually observed during states of moderate geomagnetic disturbance (Kp ~ 2-4) and their amplitudes can be as large as $2\gamma$, although a more typical (average) amplitude is 350 m$\gamma$. In addition to their diurnal variation with daytime maximum, the Pc 1b appear to have a solar cycle variation of period decreasing with decreasing solar activity. No seasonal variation has yet been derived.

Although a typical Pc 1b pulsation event consists of a single burst, series of bursts are observed on occasion. Partly for this reason, and because of other close similarities (particularly in the periods, diurnal variations, sources near the cusps, and dependence on Kp), there does not appear to be a marked difference between Pc 1b pulsations and IPRP. Thus, once again, it is desirable that this new class of pulsations be studied further, with particular attention being given to the properties that might distinguish it from IPRP. Considering the data that are available at present, I am inclined to classify the Pc 1b pulsations tentatively as a category of IPRP.

## 5. Pi 1 Pulsations (1- 40 seconds)

Pi 1 pulsations are broadband, noise-like pulsations that have an

irregular form when seen on chart records and which, by definition, occupy the period range 1-40 sec. According to Jacobs [1970], their periods as a rule are less than 15 seconds (mainly 6-10 seconds) and their amplitudes have maximum values in the auroral zones. However, these properties were deduced from Pi 1 data recorded at auroral or middle latitudes [Heacock and Chao, 1980] and do not necessarily apply to the Pi 1 pulsations that occur in the polar caps. In fact, as is the case with other classes of pulsations (except possibly for Pc 1), there have been few studies of Pi 1 pulsations in the polar caps and information on their characteristics in the polar regions is limited. The most comprehensive polar cap study is very recent [Heacock and Chao, 1980] and, insofar as this review is concerned, it suffers from one flaw: the Pi 1 and Pi 2 (40-150 sec.) categories of pulsations are treated as a single type, namely type Pi. However, it is pointed out in the study that "type Pi pulsation activity is characterized by the presence of significant energy at all frequencies from 10 to 100 mHz (T = 100-10 sec.), usually with significant contributions also at frequencies below 10 and above 100 mHz." I will therefore quote some results from this work whenever it appears that they can be applied specifically to Pi 1.

It has already been noted in this review that there can be significant pulsation activity at the geomagnetic poles when the geomagnetic field is quiet (even absolutely quiet, i.e., when Kp = 0) at auroral and middle latitudes [Heacock et al., 1970; Afonina and Fel'dshteyn,

1971]. This pulsation activity is noisy and presumably includes Pi 1 pulsations. For moderate Kp levels other classes of pulsations predominate over the Pi 1 and other irregular pulsations at the poles, but at high Kp levels the polar activity again becomes dominated by the irregular pulsations. On the whole, as pointed out by Heacock [personal communication, 1980], Pi 1 pulsations are one of the most commonly occurring forms of pulsations in the polar caps. In general, the polar Pi 1 activity does not correlate well with Pi 1 activity in the adjacent auroral zones, which indicates that the pulsations received at the poles do not simply propagate from an auroral or subauroral region via the ionosphere [Heacock et al., 1970]. On the other hand, an apparent low frequency cutoff in the range 0.1-0.3 Hz that is observed in a number of Pi 1 events suggests that ionospheric propagation can take place under some ionospheric conditions [Heacock, 1975]. These seemingly contradictory results can be reconciled if the sources of Pi 1 pulsations are of comparatively small geographical extent and are located polewards of the auroral ovals, i.e., in the polar caps.

Many details of the properties of Pi 1 pulsations in the polar caps are lacking. In particular, because the pulsations have not been measured simultaneously at a number of stations distributed over the polar caps, the spatial variation of Pi 1 amplitudes is not known. Hessler et al., [1972b] report that there is apparently a sharp dropoff in Pi 1 amplitudes within the polar regions, but quantitative

measurements of this dropoff have not been made. There is in fact one considerable difficulty that must be resolved before the spatial variation of the amplitudes and other properties of the Pi 1 pulsations can be measured in the polar regions. The difficulty arises because of the localized origin of the Pi 1 events (see the comments above). It appears likely that a comparatively dense distribution of stations is required if the spatial variations are to be measured with confidence and, unfortunately, the logistical problems that arise are immense. One possible future solution to these problems is to use automatic unmanned observatories.

Comparing Pi 1 activity in the north and south polar caps, there is as might be expected a general lack of correlation between Pi 1 events observed in the two polar regions [Hessler and Heacock, 1969]. However, similar events can be observed in the two regions on occasion [Hessler et al., 1971; Lanzerotti, 1978] and the Pi 1 activity accompanying geomagnetic storm sudden commencements is particularly likely to occur simultaneously in the two polar caps [Heacock, 1979].

The diurnal, seasonal, and solar cycle variations of Pi 1 pulsations in the polar caps are not well established, but is is known that there is a local noon enhancement at Thule during the summer months and that the winter amplitudes at Thule are substantially smaller than the summer amplitudes [Heacock and Chao, 1980]; these results presumably also apply at Vostok. The dependence on local time may help account for some of the lack of correlation between Pi 1 pulsations

in the north and south polar caps. As detailed by Heacock [1979], local noon at Thule occurs near 1640 UT, whereas local noon at Vostok occurs near 0450 UT.

The correlation between polar cap Pi 1 activity and general geomagnetic activity is not particularly well-defined. Heacock and Chao [1980] report that there is some positive correlation between the Pi 1 activity levels at Thule and Kp, but there also appears to be two components of the activity that have little correlation with Kp. One of these components is the "residual" activity that occurs at times of low Kp, and which is most marked at Thule in summer. The other component is called presubstorm activity by Heacock and Chao [1980]. There is also an additional component of the Pi 1 activity that is highly correlated with substorms.

It has long been known that Pi 1 pulsations at auroral latitudes are often strongly associated with auroral particle precipitation [Campbell, 1967]. Heacock and Chao [1980] suggest that a large component of Pi 1 pulsation activity is produced by three-dimensional magnetosphere-ionosphere current loops that are driven by the magnetospheric electric field at times of enhanced plasma convection. Independent three-dimensional current systems are postulated for various locations, including the polar caps and sites in the auroral ovals. Since the response of the current systems is related to the electrical conductivity in the E region of the ionosphere, the relation between auroral precipitation, which increases the E region conductivity, and

Pi 1 pulsations is explained by this mechanism.

Another mechanism for the generation of Pi 1 pulsations was proposed by Bol'shakova and Khorosheva [1973], following their measurements at Vostok of long-period pulsations (periods in the range 3-7 min.) on which were superposed irregular pulsations with periods of 10-100 sec. The mechanism proposed was oscillations in the magnetotail, which were assumed to modulate the intensity of auroral precipitation. This mechanism is compatible with the one proposed by Heacock and Chao [1980].

As a final note on Pi 1 pulsations in the polar caps I must mention the observation in Vostok data of discrete electromagnetic signals in the frequency range 0.1-1 Hz by Bondarenko and Gul'yel'mi [1976]. Because of their burst-like appearance and variety of forms, Bondarenko and Gul'yel'mi [1976] classified these discrete signals as Pi 1 pulsations. Dynamic spectrums of the signals show that their instantaneous mean frequency varies rapidly with time, with the variation consisting of either a monotonic increase or decrease. Most commonly the signals consist of bursts of decreasing tone.

The duration of these signals is found to average 2-3 min., although it can reach 5-10 min. in some cases, and Bondarenko and Gul'yel'mi [1976] note that the increasing tones resemble the structural elements of a pearl series, i.e., of a structured Pc 1 pulsation event. Because of the many similarities in their properties, I would classify these signals as IPRP or even as Pc 1b (which I have already suggested could perhaps be best considered as subclass of IPRP)

but not as Pi 1 pulsations.

## 6. Signals in the Lower-ELF Band (5 - 100 Hz)

Even at auroral and middle latitudes, where most measurement of naturally-occurring low-frequency electromagnetic signals have been made, the lower-ELF band has received little study compared with the various ULF bands. The situation in the polar caps for this frequency band is even worse: there is an almost total lack of data on the naturally-occurring lower-ELF signals. However, it is possible to argue that measurements at polar latitudes are unnecessary for a complete understanding of the signals in this band, since the signals that occur at high latitudes should be indistinguishable from those that occur at lower latitudes. As is well known (e.g., Campbell, 1967), the signals in the lower-ELF band differ from those of lower frequency (frequencies less that ~5 Hz ) by being generated predominantly by lightning in the earth-ionosphere cavity (possible exceptions to this rule are the natural background, which is described in a previous section, and certain whistler-like pulsation events [Heacock, 1974], both of which very probably have sources above the base of the ionosphere). The lower-ELF signals therefore propagate essentially in free space with comparatively low attenuation and little dependence on the geomagnetic field configuration. Thus the signals that occur in the polar regions should differ only slightly, if at all, from those observed at

lower latitudes. According to this argument, measurements in the polar regions on the lightning-generated signals are superfluous.

Interestingly, the one study I have been able to locate of the lightning-generated signals in the polar caps provides support for this argument. Following measurements of the natural electromagnetic activity in the frequency range 5-40 Hz at ten widely spaced stations (two which were in the northern polar cap), Shand [1965] found that (1) with few exceptions, a burst recorded at one station was received at all other stations regardless of their spacing, (2) neither power spectrum plots nor analog traces (i.e., strip chart records) revealed conspicuous differences in signal strength or frequency content between mid, auroral, and polar cap latitudes, and (3) no evidence of ELF activity from a high latitude source was found.

Despite these valuable results, it still appears important for further measurements to be made in the lower-ELF range in the polar caps. Two reasons for continuing these measurements are immediately apparent. First, the whistler-like pulsation events discovered by Heacock [1974] occur predominantly in the frequency range 40-120 Hz, and thus they were not included in the measurements made by Shand [1965]. As I have pointed out, these pulsations, together with much of the natural background (as defined by Fraser-Smith and Buxton [1975], are likely to have sources above the base of the ionosphere and they could well have unexpected properties in the polar caps. The whistler-like pulsation events look particularly promising for study in the

polar caps: they have only been detected at a single high-latitude (auroral) location and they lack echoes, which suggests a possible origin on open geomagnetic field lines. A second reason for lower-ELF measurements in the polar caps is the occurrence of unique polar cap ionospheric changes in response to solar proton events (and possibly other solar phenomena as well). These ionospheric changes can affect the lightning-generated lower-ELF signals significantly [e.g., Fraser-Smith and Helliwell, 1980] and conceivably they may also affect the component of lower-ELF activity that is not generated by lightning.

## IV. DISCUSSION

I have assumed in this review that the ULF/lower-ELF pulsations have identical properties in the two polar caps. In practice, some properties of the pulsations may not be identical due to differences in the overall effective electrical conductivity of the "ground" in the two regions. If there are such differences, which is likely, the electric currents and resulting electromagnetic fields induced by the same incident pulsations will differ, and the total electric and magnetic fields (incident pulsation fields plus induced fields), which are the quantities that are measured, will reflect the difference. Perhaps more important, gradients or discontinuities of electrical conductivity near pulsation measurement sites can also influence the pulsation fields and thus conceivably produce spurious differences in the properties of pulsations observed in the northern and southern polar caps. These possibilities are not merely academic since they are relevant to comparisons of ULF/lower-ELF pulsation data recorded at the two principal polar cap stations, Thule and Vostok. Thule, near the northern geomagnetic pole, is located near the coast of Greenland and pulsations measured at this station are subject to a "coastal effect" [e.g. Parkinson, 1962; Weaver, 1963; Gregori and Lanzerotti, 1979], which is caused by the sea-land electrical conductivity discontinuity. Vostok, near the southern geomagnetic pole, is located well away from the coast of Antarctica and there should be no coastal effect at the ULF/lower-ELF frequencies considered in this work. The properties of a particular class of pulsations observed at Thule may therefore

differ in some respects from the properties of the same class of pulsations observed at Vostok.

However, the changes in the apparent properties of pulsations caused by ground conductivity, or by gradients and discontinuities of ground conductivity, should not be overemphasized. Corrections for the effects of the ground can be made, if necessary, and for some pulsation properties it may be possible to ignore the ground effects. Care is needed in comparing the amplitudes and polarizations of the electric and magnetic fields of the pulsations, for example, but other important properties of the pulsations, such as their occurrence rates, frequency characteristics, and diurnal and seasonal variations are less likely to be affected directly.

No results from drifting ice stations are included in this review, even though these stations have provided useful information about the electromagnetic fields in the northern polar cap in the past [e.g., Zhigalov and Zhigalova, 1961; Novysh and Fonarev, 1963, 1966] and they are likely to continue to do so in the future. It turns out that the available measurements were either made outside the polar caps [e.g., Steg, 1961] or they did not cover the appropriate frequency range (0.022-100 Hz). There is a problem making measurements in this frequency range on drifting ice stations because the most sensitive magnetometers (induction loop and superconducting magnetometers) are motion sensitive and the ice stations are subject to noisy motion from ordinary ice movements (the bumping, scraping, and so on of ice floes)

and substantial periodic motion that is at least partly generated by wind action and which has frequencies in the range 0.022-10 Hz [Hunkins, 1963]. It is therefore of considerable interest to see that the suitability of artic sea ice as a platform for measuring ULF/lower-ELF electromagnetic signals with induction magnetometers has been studied by Shand [1964]. The results of this study are not encouraging for measurements on the open Arctic Ocean, but they suggest that land-locked polar ice may be adequately stable to support sensitive induction magnetometer measurements.

There are a large number of different pulsation phenomena in the polar caps and some confusion between the various categories or subcategories is perhaps inevitable. Apart from the serpentine emissions, which can be classified as a class of unstructured Pc 1 pulsations with reasonable confidence, there appear to be two particular kinds of pulsations that may cause classification problems at the present time. The first of these is the category of unstructured Pc 1 pulsations, which straddles the formal Pc 1 and Pc 2 frequency ranges and which appears to constitute the entire class of Pc 2 pulsations when its frequencies are in the appropriate range. Provided the existence of this category of pulsations is recognized ("unstructured Pc 1-2 pulsations"), it should present only a minor problem of classification. More difficult to resolve is the apparent confusion between the IPRP (or PVP) and Pc 1b categories of pulsations. These pulsations have many features in common and I believe they could be classified into one

category, possibly called "Pc 1-2 pulsation bursts". To assist in the classification or identification of these various pulsations, it would be particularly useful to have on hand an atlas of polar cap ULF/lower-ELF pulsation spectrums similar to the more general atlas prepared by Heacock [1970].

This review has emphasized the gaps in our knowledge of the ULF/lower-ELF signals that occur in the polar caps. Even when there are no gaps, and measurements have been made, there are often uncertainties in the results due to the limited time over which the measurements were made or to the limited distribution of stations. There are therefore many opportunities for original studies of ULF/lower-ELF activity in these remote regions. Considering the number of new polar cap pulsation phenomena reported by Soviet scientists in the last decade alone, there also appear to be more than average opportunities for new discoveries during the course of these studies.

One may question why there have been so few studies of ULF/lower-ELF pulsations in the polar caps by scientists from western nations. With the exception of the investigators cited in this review from the University of Alaska, scientists from the Soviet Union have provided the initiative in these studies for many years. The logistical problems are very great, but there are still a considerable number of permanent stations in the Antarctic that are located in the southern polar cap and which are accessible to all scientists. There are also a number of reasonably accessible permanent stations in the Arctic polar cap.

Perhaps, as the opportunities for original research on naturally-occurring ULF/lower-ELF electromagnetic signals at middle and auroral latitudes become increasingly limited, there will be a reassessment of the direction of this research and more emphasis will be given to exploratory research at the frontiers of knowledge. In the case of ULF/lower-ELF pulsations, these frontiers are located in the polar caps.

## V. REFERENCES


Afonina, R.G., and Ya.I. Fel'dshteyn, "Relationship between geomagnetic field variations in the polar region and in the morning-night sectors of the auroral oval", Geomag. Aeron. USSR, English Transl., 11, 485-487, 1971.

Akasofu, S.-I., and S. Chapman, Solar-Terrestrial Physics, Oxford University Press, 1972.

Axford, W.I., "The polar wind and the terrestrial helium budget", J. Geophys. Res., 73, 6855-6859, 1968.

Banks, P.M., and T.E. Holzer, "The polar wind", J. Geophys. Res., 73, 6846-6854, 1968.

Baranskiy, L.N., T.A. Plyasova-Bakunina, K.R. Ramanudzhachari, L.V. Sobolev, and V.I. Selivanov, "Distribution of the intensity of Pc 3-4 pulsations along the geomagnetic meridian", Geomag. Aeron. USSR, English Transl., 13, 924-928, 1973.

Baranskiy, L.N., T.A. Plyasova-Bakunina, P.A. Vinogradov, G.A. Loginov, and A.N. Popov, "Distribution of the intensity of geomagnetic Pc 3 pulsations over the Eurasian continent", Geomag. Aeron. USSR, English Transl., 14, 280-282, 1974.

Bobrov, M.S., N.F. Koroleva, and R.M. Novikova, "The properties of the solar wind from permanent geomagnetic disturbances on days with rather low Kp", Geomag. Aeron. USSR, English Transl., 4, 259-264, 1964.




PRECEDING PAGE BLANK-NOT FILMED

Bol'shakova, O.V., and A.V. Gul'yel'mi, "Penetration of hydromagnetic waves from the tail of the magnetosphere into the polar cap", Geomag. Aeron. USSR, English Transl., 12, 505-507, 1972.

Bol'shakova, O.V., and O.V. Khorosheva, "Zonal nature of certain disturbances of micropulsations at the geomagnetic pole", Geomag. Aeron. USSR, English Transl., 13, 294-297, 1973.

Bol'shakova, O.V., V.A. Troitskaya, and V.P. Hessler, "Determination of the position of the polar boundary of the day cusp from the intensity of high-latitude pulsations", Geomag. Aeron. USSR, 15, 569-570, 1975.

Bol'shakova, O.V. and V.A. Troitskaya, "Dynamics of the day cusp, according to observations of long-period geomagnetic pulsations", Geomag. Aeron. USSR, English Transl., 17, 722-725, 1977.

Bondarenko, N.M., and A.V. Gul'yel'mi, "Discrete electromagnetic signals in the range of $\sim 0.1 - 1$ Hz in the polar cap", Geomag. Aeron. USSR, English Transl., 16, 184-186, 1976.

Buloshnikov, A.M., M.B. Gokhberg, Yu. A. Kopytenko, Yu.P. Novikov, O.M. Raspopov, and V.A. Troitskaya, "Characteristics of the spatial distribution of geomagnetic Pc 3 pulsations at the surface of the earth", Geomag. Aeron. USSR, English Transl., 17, 760-762, 1977.

Cagniard, L., "Basic theory of the magneto-telluric method of geophysical prospecting", Geophysics, 18, 605-635, 1953.

Campbell, W.H., "Geomagnetic pulsations", in Physics of Geomagnetic Phenomena, Vol. 2, 821-909, eds. S. Matsushita and W.H. Campbell, Academic Press, N.Y., 1967.

Campbell, W.H., "Spectral composition of geomagnetic field variations in the period range of 5 min to 2 hr as observed at the earth's surface", Radio Sci., 8, 929-932, 1973.

Campbell, W.H., "An analysis of the spectra of geomagnetic variations having periods from 5 min to 4 hours", J. Geophys. Res., 81, 1369-1390, 1976.

Campbell, W.H., "Polar cap geomagnetic field responses to solar sector changes", J. Geophys. Res., 81, 4731-4744, 1976.

Chubb, T.A., and G.T. Hicks, "Observations of the aurora in the far ultraviolet from OGO 4", J. Geophys. Res., 75, 1290-1311, 1970.

Dacosta, A., and B.V. Dovbnya, "Sporadic emission in the polar cap in the 0.1- to 0.7-Hz range during sudden magnetic storm commencements", Geomag. Aeron. USSR, English Transl., 14, 948-950, 1974.

Davidson, M.J., "Average diurnal characteristics of geomagnetic power spectrums in the period range 4.5 to 1000 seconds", J. Geophys. Res., 69, 5116, 1964.

Davies, K., Ionospheric Radio Waves, p. 72, Blaisdell, Mass., 1969.

Dubrovskiy, V.G., and S.A. Kramarenko, "Spectral characteristics of

the terrestrial and interplanetary magnetic fields in the frequency range 1 to $10^{-4}$ Hz", Geomag. Aeron. USSR, English Transl., 11, 884-889, 1971.

Fel'dshteyn, Ya.I., "Some problems concerning the morphology of auroras and magnetic disturbances at high latitudes", Geomag. Aeron. USSR, English Transl., 3, 183-192, 1963.

Fraser-Smith, A.C., "Short-term prediction and a new method of classification of Pc 1 pulsation occurrences", Planet. Space Sci., 28, 739-747, 1980.

Fraser-Smith, A.C., and J.L. Buxton, "Superconducting magnetometer measurements of geomagnetic activity in the 0.1- to 14-Hz frequency range", J. Geophys. Res., 3141-3147, 1975.

Fraser-Smith, A.C., and R.A. Helliwell, "ELF sferic occurrences in the Antarctic during a solar proton event: case study of occurrences at Byrd Station during the event of June 9, 1968", J. Geophys. Res., 85, 2296-2306, 1980.

Gendrin, R., S. Lacourly, V.A. Troitskaya, M. Gokhberg, and R.V. Shepetnov, "Caracteristiques des pulsations irregulieres de periode decroissante (I.P.D.P.) et leurs relations avec les variations du flux des particules piegees dans la magnetosphere", Planet. Space Sci., 15, 1239-1259, 1967.

Gendrin, R., and S. Lacourly, "Irregular micropulsation and their

relations with the far magnetospheric perturbations", Ann. Géophys., 24, 1-7, 1968.

Gregori, G.P., and L.J. Lanzerotti, "The effect of coast lines on geomagnetic measurements: A commentary", Rivista Ital. di Geofisica, 5, 81-86, 1979.

Gregori, G.P., and L.J. Lanzerotti, "Geomagnetic depth sounding by induction arrow representation: A review", Rev. Geophys. Space Phys., 18, 203-209, 1980.

Greifinger, C., and P.S. Greifinger, "Theory of hydromagnetic propagation in the ionospheric waveguide", J. Geophys. Res., 73, 7473-7490, 1968.

Gul'yel'mi, A.V., and B.V. Dovbnya, "Observation of geomagnetic pulsations in the 0- to 2-Hz range with intense modulation of the carrier frequency", Geomag. Aeron. USSR, English Transl., 14, 740-742, 1974.

Heacock, R.R., "An atlas of micropulsation spectra", Rep. UAG R-214, Univ. of Alaska, College, Alaska, August 1970.

Heacock, R.R., "Whistler-like pulsation events in the frequency range 20 to 200 Hz", Geophys. Res. Lett., 1, 77-79, 1974.

Heacock, R.R., "F-layer duct propagation of hydromagnetic waves in the polar cap ionosphere", Antarctic J., 10, 220-221, 1975.

Heacock, R.R., "Asymmetries in magnetic field pulsation activity observed simultaneously in southern and northern polar caps", Antarctic J., 14, 219-220, 1979.

Heacock, R.R., and V.P. Hessler, "Pearl-type micropulsations associated with magnetic storm sudden commencements", J. Geophys. Res., 70, 1103-1111, 1965.

Heacock, R.R., V.P. Hessler, and J.K. Olesen, "The 2- 0.1 Hz polar cap micropulsation activity", J. Atmos. Terr. Phys., 32, 129-138, 1970.

Heacock, R.R., and M. Kivinen, "Type Pc 1 micropulsation activity at high latitudes", pp. 1-52 in Polar Micropulsation, Eds. V.P. Hessler and V.A. Troitskaya, Rep. UAG R-220, Geophys. Insti., Univ. of Alaska, College, Alaska, May 1972.

Heacock, R.R., and S.-I. Akasofu, "Periodically structured Pc 1 micropulsations during the recovery phase of intense magnetic storms", J. Geophys. Res., 78, 5524-5536, 1973.

Heacock, R.R., and J.K. Chao, "Type Pi magnetic field pulsations at very high latitudes and their relation to plasma convection in the magnetosphere", J. Geophys. Res., 85, 1203-1213, 1980.

Hessler, V.P., "Magnetic micropulsation activity at the south geomagnetic pole", Antarctic J., 2, 256-258, 1967.

Hessler, V.P., and R.R. Heacock, "Micropulsation studies in the polar

caps", Antarctic J., 4, 225-226, 1969.

Hessler, V.P., R.R. Heacock, and V.A. Troitskaya, "Micropulsations at geomagnetic poles", Antarctic J., 6, 226-227, 1971.

Hessler, V.P., R.R. Heacock, and V.A. Troitskaya, "Micropulsations at the geomagnetic poles, 1971", Antarctic J., 7, 157-158, 1972a.

Hessler, V.P., R.R. Heacock, J. Olesen, C. Sucksdorff, and J. Kangas, "Micropulsations associated with polar magnetic substorms", pp. 84-167, in Polar Micropulsations, Eds. V.P. Hessler and V.A. Troitskaya, Rep. UAG R-220, Geophys. Inst., Univ. of Alaska, College, Alaska, May, 1972b.

Hope, E.R., "Low-latitude and high-latitude geomagnetic agitation, J. Geophys. Res., 66, 747-776, 1961.

Hunkins, K., "Waves on the Arctic Ocean", J. Geophys. Res., 67, 2477-2489, 1962.

Jacobs, J.A., "Micropulsations of the earth's electromagnetic field in the frequency range 0.1 - 10 cps". in Natural Electromagnetic Phenomena below 30 Kc/s, pp. 319-349, Ed. D.F. Bleil, Plenum Press, New York, 1964.

Jacobs, J.A., "Geomagnetic Micropulsations", 179 pp., Springer, New York, 1970.

Jacobs, J.A., and K. Sinno, "Occurrence frequency of geomagnetic micropulsations, Pc", J. Geophys. Res.,65, 107-113, 1960.

Jacobs, J.A., Y. Kato, S. Matsushita, and V.A. Troitskaya, "Classification of geomagnetic micropulsation", J. Geophys. Res., 69, 180-181, 1964.

Kovner, M.S., and V.A. Kuznetsova, "Possible generation mechanism of low-frequency pulsations in the polar cusp", Geomag. Aeron. USSR, English Transl., 17, 726-728, 1977.

Lanzerotti, L.J., "Studies of geomagnetic pulsations", pp. 130-156 in Upper Atmosphere Research in Antarctica, Eds. L.J. Lanzerotti and C.G. Park, Vol. 29 of Antarctic Research Series, American Geophys. Union, Washington D.C., 1978.

Lanzerotti, L.J., and C.G. Park, (Editors), Upper Atmosphere Research in Antarctica, p. 263, American Geophys. Union, Washington D.C., 1978.

Manchester, R.N., "Propagation of Pc 1 micropulsations from high to low latitudes", J. Geophys. Res., 71, 3749-3754, 1966.

Mansurov, S.M., "New evidence of a relationship between magnetic fields in space and on the earth", Geomag. Aeron USSR, English Transl., 9, 622-623, 1969.

Matveyeva, E.T., and V.A. Troitskaya, "General patterns of pearl-type pulsations", Geomag. Aeron. USSR, English Transl, 5, 846-850, 1965.

Matveyeva, E.T., V.A. Troitskaya, and F.Z. Feygin, "Intervals of geomagnetic pulsations of variable period in the polar caps", Geomag.

Aeron. USSR, English Transl., 16, 187-189, 1976a.

Matveyeva, E.T., V.A. Troitskaya, and F.Z. Feygin, "Intervals of pulsations with rising periods (IPRP) in polar caps", Planet. Space Sci., 24, 673-678, 1976b.

Matveyeva, E.T., V.A. Troitskaya, and F.Z. Feygin, "Isolated bursts of type Pc 1b geomagnetic pulsations at high latitudes", Geomag. Aeron. USSR, English Transl., 18, 75-78, 1978.

Mayaud, P.N., "Activité magnétique dans les régions polaires", Ann. Géophys., 12, 84-101, 1956.

McPherron, R.L., "Magnetospheric substorms", Rev. Geophys. Space Sci., 17, 657-681, 1979.

McPherron, R.L., and S.H. Ward, "Correlation between occurrence of pearl pulsations and interplanetary magnetic field sector boundaries", J. Geophys. Res., 72, 393-398, 1967.

Nishida, A., Geomagnetic Diagnosis of the Magnetosphere, 256 pp., Springer, New York, 1978.

Novysh, V.V., and G.A. Fonarev, "Telluric currents in the Arctic Ocean", Geomag. Aeron. USSR, English Transl., 3, 919-921, 1963.

Novysh, V.V., and G.A. Fonarev, "Some results of electromagnetic investigations in the Arctic Ocean", Geomag. Aeron. USSR, English Transl., 6, 325-327, 1966.

Orr, D., "Magnetic pulsations within the magnetosphere: A review",

J. Atmos. Terr. Phys., 35, 1-50, 1973.

Parkinson, W.D., "The influence of continents and oceans on geomagnetic variations", Geophys. J. Roy. Astron. Soc., 6, 441-449, 1962.

Patel, V.L., "Solar-terrestrial physics", pp. 159-193 in Illustrated Glossary for Solar and Solar-Terrestrial Physics, Eds. A. Bruzek and C.J. Durrant, D. Reidel, Dordrecht, Holland, 1977.

Polk, C., "Sources, propagation, amplitude and temporal variation of extremely low frequency (0-100 Hz) electromagnetic fields", pp. 21-48, in Biologic and Clinical Effects of Low-Frequency Magnetic and Electric Fields, Eds. J.G. Llaurado, A. Sances, Jr., and J.H. Battocletti, C.C. Thomas, Springfield, Illinois, 1974.

Reid, G.C., "Polar cap absorption - observation and theory", in Handbook of Astronomy, Astrophysics and Geophysics, Vol. 1, Eds. C.W. Gordon, V. Canuto, and W.I. Axford, pp. 269-302, Gordon and Breach, New York, 1978.

Saito, T., "Geomagnetic pulsations", Space Sci. Rev., 10, 319-412, 1969.

Scarf, F.L., R.W. Fredericks, I.M. Green, and C.T. Russell, "Plasma waves in the dayside polar cusp 1. Magnetospheric observations", J. Geophys. Res., 77, 2274-2293, 1972.

Scarf, F.L., R.W. Fredericks, M. Neugebauer, and C.T. Russell, "Plasma waves in the dayside polar cusp 2. Magnetopause and polar magnetosheath", J. Geophys. Res., 79, 511-520, 1974.

Shand, J.A., "On the suitability of arctic sea ice as a platform for measuring electromagnetic background at micropulsation and extremely low frequencies", Tech. Mem. 64-7, Pacific Naval Lab., Esquimalt, B.C., August 1964.

Shand, J.A., "A review of PNL observations of the Schumann- ELF natural electromagnetic background", Tech. Mem. 65-6, Pacific Naval Lab., Esquimalt, B.C., October 1965.

Shchepetnov, P.V., and A.L. Kalisher, "Some correlations of the interval of pulsations of decreasing period on February 12, 1964, "Geomag. Aeron. USSR, English Transl., 8, 151-153, 1968.

Stagg, J.M., "Numerical character-figures of magnetic disturbance in relation to geomagnetic latitude", Terr. Mag. Atmos. Elect., 40, 255-262, 1935.

Steg, R.G., "Electromagnetic noise measurements in the Arctic", Tech. Mem. 941.1-47-61, U.S. Navy Underwater Sound Lab., New London, Connecticut, 12 June 1961.

Stuart, W.F., V.E. Sherwood, and S.M. MacIntosh, "The power spectral density technique applied to micropulsation analysis", Pure Appl. Geophys., 92, 150-164, 1971.

Surkan, A.J., and L.J. Lanzerotti, "ULF geomagnetic power near L=4, 3. Statistical study of power spectra in conjugate areas during December solstice", J. Geophys. Res., 79, 2403-2412, 1974.

Svalgaard, L., "Sector structure of interplanetary magnetic field and daily variation of the geomagnetic field at high latitudes", Geophys. Pap. R6, pp. 1-11, Dan. Meteorol. Inst., Copenhagen, 1968.

Temerin, M., and B. Parady, "Observations of ULF electric field fluctuations in the dayside auroral oval", J. Geophys. Res., 85, 2925-2934, 1980.

Tepley, L., "Low-latitude observations of fine-structured hydromagnetic emissions", J. Geophys. Res., 69, 2273-2290, 1964.

Tepley, L.R., and K.D. Amundsen, "Observations of continuous sub-ELF emissions in the frequency range 0.2 to 1.0 cycles per second", J. Geophys. Res., 70, 234-239, 1965.

Tepley, L.R., and R.K. Landshoff, "Waveguide Theory for ionospheric propagation of hydromagnetic emissions", J. Geophys. Res., 71, 1499-1504, 1966.

Thomson, D.J., M.F. Robbins, C.G. Maclennan, and L.J. Lanzerotti, "Spectral and windowing techniques in power spectral analyses of geomagnetic data", Phy. Earth and Planet. Interiors, 12, 217-231, 1976.

Tikhonov, A.N., "On determining the electrical properties of the earth's crust", Dokl. Akad. Nauk SSSR, 73, 295-310, 1950.

Troitskaya, V.A., "Pulsations of the earth's electromagnetic field with periods of 1 to 15 seconds and their connection with phenomena in

the high atmosphere", J. Geophys. Res., 66, 5-18, 1961.

Troitskaya, V.A., "Micropulsations and the state of the magnetosphere", pp. 213-274, in Solar-Terrestrial Physics, eds. J.W. King and W.S. Newman, Academic Press, London, 1967.

Troitskaya, V.A., "Geomagnetic pulsations in the polar cap", pp. 121-123 in Magnetospheric Study 1979, Proc. Int. Workshop on Select. Topics of Magnetospheric Phys., Japanese IMS Comm., Tokyo, 1979.

Troitskaya, V.A., O.V. Bolshakova, and V.P. Hessler, "Preliminary results of micropulsation studies at magnetoconjugate points in the Arctic and Antarctic", Ann. Géophys., 24, 741-746, 1968.

Troitskaya, V.A., O.V. Bolshakova, and V.P. Hessler, "Main regularities of micropulsations at the geomagnetic poles", pp. 53-83, in Polar Micropulsations, Eds. V.P. Hessler and V.A. Troitskaya, Rep. UAG R-220, Geophys. Inst., University of Alaska, College, Alaska, May 1972.

Weaver, J.T., "The electromagnetic field within a discontinuous conductor with reference to geomagnetic micropulsations near a coastline", Canadian J. Phys., 41, 484-495, 1963.

Wertz, R., and W.H. Campbell, "Integrated power spectra of geomagnetic field varations with periods of 0.3-300 s", J. Geophys. Res., 81, 5131-5140, 1976.

Wescott, E.M., V.P. Hessler, and J.F. Kenney, "Hydromagnetic emissions

at the geomagnetic poles", Nature, 212, 170-171, 1966.

Wilcox, J.M., "Inferring the interplanetary magnetic field by observing the polar geomagnetic field", Rev. Geophys. Space Phys., 10, 1003-1014, 1972.

Yudovich, L.A., "Magnetic activity at the geomagnetic poles during the IGY period", Geomag. Aeron. USSR, English Transl., 2, 922-929, 1962.

Zhigalov, L.N., and N.N. Zhigalova, "The distribution of magnetic activity in a narrow sector of longitudes in the eastern arctic", Geomag. Aeron. USSR, English Transl., 1, 62-67, 1961.

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